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Coherent Fiber-Optic Links for Transmission and Signal Processing in Microwave and Millimeter-Wave Systems

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Abstract

The principles of coherent fiber-optic links are presented and the transmission and signal processing capabilities offered to microwave and millimeter-wave systems are discussed. Furthermore, an overview of implemented transmitter types and link experiments is given.

1. Introduction

Fiber-optic links are gaining increasing interest for implementation of transmission as well as signal processing functions in microwave and millimeter-wave systems.

The basic outline for a fiber-optic link is shown in Fig. 1. Basically, the link transports a signal from its input to its output. If the signal remains unaltered, the link is transparent and its only function is signal transmission. On the other hand, if the signal is intentionally altered by the link, it also performs signal processing. This added functionality may be desirable in many systems and may enable a number of new applications. At present, the potential of such multifunctional links is increasingly recognized [1]-[6]. In coherent links, the signal processing functions can most often be obtained without significant added complexity and cost and without degradation of the transmission performance.

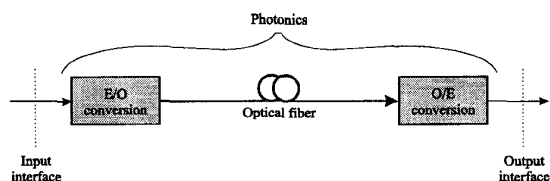


Figure 1: Schematic for the fiber-optic link.

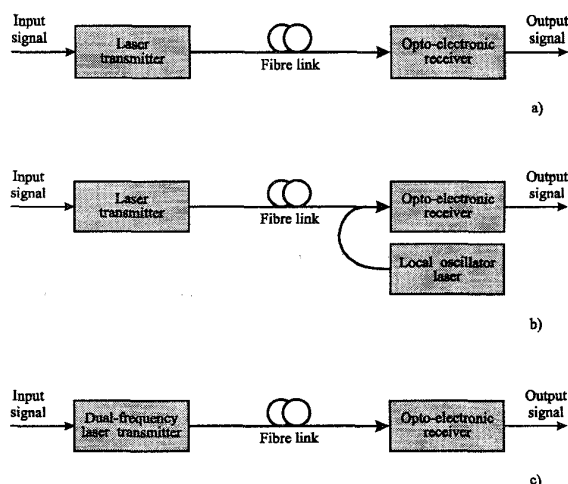


Figure 2: Schematics for a) IM-DD links, b) HD coherent links, and c) RHD coherent links.

2. Principles of coherent links

Fiber-optic links may be implemented with coherent or non-coherent techniques. The three resulting link types are shown in Fig. 2. A detailed description of the non-coherent intensity modulated direct detection (IM-DD) link type can be found in [7], [8]. In the heterodyne detection (HD) and the remote heterodyne detection (RHD) links, the interaction between two laser signals form the basis for the detection process, and the detected signal current is given as

$$i_s(t) = 2R\sqrt{p_1(t)p_2(t)} \cdot \cos[\{\omega_1(t) - \omega_2(t)\}t + \phi_1(t) - \phi_2(t)]$$

where R is the responsivity of the photodetector,

t is the time, and $p(t)$ is the instantaneous power, $\omega(t)$ is the instantaneous frequency and $\phi(t)$ is the instantaneous phase of the laser signals. The equation shows that it is necessary to maintain a well defined correlation between the frequency and phase of the two signals. This makes coherent links more complex than non-coherent links. However, as discussed in this paper, it also offers a number of advantages. More detailed descriptions of the HD principle can be found in [9] and of the RHD principle in [5], [6], [8].

This paper is focused on RHD coherent links. In these, both laser signals are generated at the transmitter end of the link. This makes it significantly easier to maintain frequency and phase correlation as compared to HD links.

3. Transmission capabilities

The transmission properties and capabilities of coherent RHD links are, in many respects, different from those of the IM-DD links. The higher complexity of coherent links pays off in terms of:

- Higher link gain [10].
- Comparable or higher linearity [10].
- Comparable or higher CNR [10].
- Lower sensitivity to chromatic dispersion [8].

The link gain can be much higher since a modulation depth of unity can be achieved without degradation of linearity (see the equation) and since the power from two lasers is often involved. The CNR improvement depends on the involved noise sources. Incorporation of optical pre-amplifiers in the DD receivers will reduce the CNR advantage offered by the coherent detection.

4. Signal processing capabilities

In addition to attractive transmission capabilities, the coherent links readily offer photonic signal processing possibilities. This is evident from the equation where it is seen that changes in either amplitude, frequency or phase applied to one of the laser signals will result in proportional changes of the signal at the output of the link.

This feature opens up for photonic implementation of a variety of functionalities in microwave and millimeter-wave systems:

- Transmission.
- Amplitude control.
- Frequency control.
- Phase control.
- Time delay control.
- Filtering.
- Modulation and demodulation.
- Frequency conversion.
- Signal recovery.

Photonic implementation of these functionalities may be advantageous in some existing applications and may open up for new applications that were not possible beforehand.

All of the listed functionalities are, to a large extent, equally important. It is, however, impossible to give a complete survey of them all. In the remainder of the paper, which deals with experimental results, the focus is placed on transmitter concepts and RHD link experiments demonstrating transmission, modulation, frequency conversion and signal recovery.

5. Dual-frequency laser transmitters

The RHD links require dual-frequency laser transmitters. These can be implemented in different ways and a significant number of concepts have been proposed and experimented:

- Dual mode laser (DML) transmitters [11].
- Pulsed laser (PL) transmitters [12].
- Optical frequency shifter (OFS) transmitters:
 - Splitting and shifting (SS) [13], [14].
 - SSB modulation [15]-[17].
 - Suppressed carrier DSB modulation [18].
- Optical injection locked loop (OILL) transmitters [19]-[21].
- Optical phase locked loop (OPLL) transmitters [22]-[25].
- Optical feedforward modulator (OFFM) transmitters [26].

The above transmitters, some of which are conceptually very different, basically generate two phase correlated optical signals that can be separately altered in intensity, frequency and phase. All of them have been successfully used in link experiments.

Table 1: Overview of RHD link transmission and signal processing experiments.

Functionality	Tx concept	LF	IF	RF	Modulation	Year	Ref.
Modulation	OPLL	1 Gb/s		9 GHz	1 Gb/s QPSK	1994	[27]
Modulation	OFS-DSB	140 Mb/s		36 GHz	140 Mb/s BPSK	1994	[28]
Up-conversion	OFS-SSB		50 MHz	650 MHz	No modulation	1994	[29]
Up-conversion	OPLL		2 GHz	9 GHz	100 Mb/s DPSK	1994	[30]
Up-conversion	PL		2 GHz	58 GHz	155 mb/s BPSK	1996	[31]
Up-conversion	OFS-SSB		2 GHz	39 GHz	155 mb/s BPSK + AM-VSB	1997	[32]
Up-conversion	OILL		140 MHz	19 GHz	140 Mb/s OQPSK	1997	[20]
Up-conversion	OILL		1 GHz	64 GHz	140 Mb/s OQPSK	1998	[33]
Transparency	OFFM			39 GHz	300 Mb/s BPSK	1994	[34]
Transparency	DML			60 GHz	No modulation	1996	[11]
Transparency	OFS-SSB			12 GHz	51.8 Mb/s BPSK	1997	[35]
Transparency	OFS-SSB			38.1 GHz	155 Mb/s BPSK	1997	[36]
Transparency	OFS-SSB			10 GHz	2.49 Gb/s BPSK	1997	[37]
Transparency	DML			36.8 GHz	51.8 Mb/s PSK	1998	[38]
Signal recovery	OPLL			7.6 GHz	27 MHz FM	1994	[39]

6. Link experiments

An overview of the link experiments that have been carried out using coherent RHD is given in Table 1. A large number of different functionalities, transmitter concepts and signal formats have been experimented with excellent results. For all of the experiments, the indicated functionality describes the signal processing that is carried out by the link in addition to transmission.

All of the transmitter concepts have been applied although not for all functionalities. As an example, it is only the OPLL transmitter that can be used for transparent signal recovery of a microwave signal that has been degraded by additive noise [5], [39].

The SSB modulation transmitter is by far the most popular. This is because of its lower complexity as compared to especially the OILL and OPLL transmitters. However, the latter do enable a better performance in terms of link gain and CNR without the addition of optical amplifiers. This is because the full power from two separate lasers is ideally available for transmission. Furthermore, the two laser signals are readily available for individual photonic processing.

The experiments clearly demonstrate the feasibility of coherent fiber-optic RHD links. As evident, most focus on transparent transmission and frequency conversion. However, the photonic signal processing potential of coherent links can be taken much further. This may lead to many new innovative system applications.

7. Conclusion

Coherent fiber-optic RHD links exhibit attractive transmission capabilities as compared to IM-DD links. In addition, they also offer the capabilities to perform a large number of different signal processing functionalities. An overview of link experiments demonstrating, modulation, frequency conversion, and signal recovery has been given. In many applications, such links may be much more desirable than transparent links. As opposed to the conventional DD links, the RHD links can in many cases be optimized to the specific application. This may significantly influence performance, cost, power consumption, etc. When comparing DD links and RHD links this must be taken into account, and the entire system must be evaluated in its entirety from end-to-end.

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